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Influence of local friction coefficient and strain hardening on the scratch resistance of polymeric surfaces investigated by finite element modeling

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Abstract

In this study, we propose the mechanical analysis of contact between a rigid spherical indenter and an amorphous polymeric surface during scratching. Experimental scratch tests, using our specific experimental set-up, allowing in situ observation of the contact area and also of the residual groove, have clearly shown the influence both of the local friction and the strain hardening of the tested surface. A 3D finite element modelling (FEM) of the corresponding scratch tests has been developed by assuming a two segments simplified constitutive law, a linear elastic behaviour followed by a linear strain hardening. The friction at the interface between the indenter and the material was modelled with a Coulomb's friction coefficient varying between 0 and 0.5, and the ratio a/R was fixed at a constant value of 0.3 to simulate elastic-plastic contacts. Evolutions of the apparent friction coefficient and of the contact pressure are presented.

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1. Introduction

Due to their much desired properties, bulk polymeric materials are increasingly used for many applications in industry, for example, as interior and exterior materials in the automobile industry as

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replacement for many metals parts. For many applications, it is well known that good appearance is a key attribute. However, good appearance is directly related to the scratch and mar resistance of surfaces. Hence, single probe testing techniques [1-3], including scratch tests, are widely employed now in studying tribological and mechanical properties of polymeric materials. However, these different mechanical tests on polymeric surfaces have been used with limited success and primarily for qualitative comparisons and quality control. Moreover, scratch and mar behaviour is not only related to the surface properties but also to the associated loading conditions, such as the tip geometry, scratch velocity, loading rates during indentation, and scratch phases. However, even if the number of scratch tests variables is important, robust methods to identify the effective and local rheological properties at the micrometer and sub-micrometer length scales are needed, for a better understanding of the frictional, abrasive, and scratch resistance of polymeric surfaces.

Recently, Gauthier and Schirrer [3] have developed a specific micro-indentation and micro-scratch tester, adapted to the mechanical characterization of amorphous transparent polymers, such as thermoplastic or thermoset resins. This single probe scratch device allows in-situ observations both of the contact area between the moving tip and the tested surface, but also the residual groove formed at the rear part of the indenter during scratch experiment, as shown by the different optical micrographs in Fig. 1. Such optical micrographs show that the contact geometry between a spherical tip the deformed surface during scratch test is complex, with the formation of lateral and frontal pile-up pads, and also a more or less important elastic recovery of the groove, as a function of the tested material, the friction coefficient and the scratching conditions.

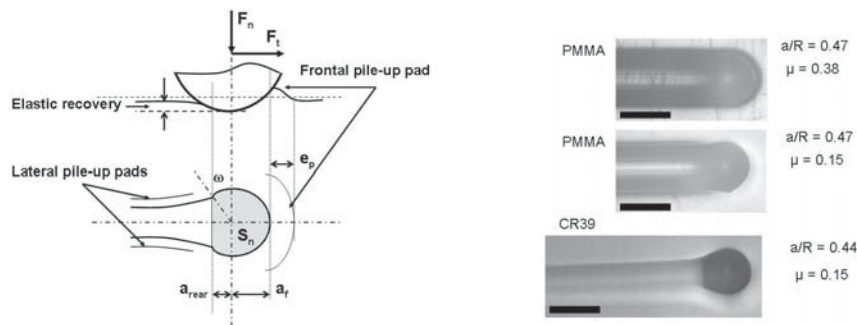


Fig. 1. (a) Schematic illustration of the contact geometry between a scratching tip and a polymeric surface; (b) optical observations of scratch experiments performed onto two different polymers.

Using three-dimensional (3D) finite element modeling (FEM), we propose for elastic-plastic contacts during scratch to show the influence of the local friction coefficient and the strain hardening ability of the tested material on the definition of an equivalent average plastic strain, but also on the evolution the apparent friction coefficient.

2. Experimental details

Numerical simulations are required in order to improve interpretations of scratch into bulk materials and bilayer systems [4-6]. Hence, scratch tests for a spherical indenter with a radius R was modeled using a 3D finite element code at a given penetration depths h to reproduce a ratio a/R of about 0.3. All calculations were carried out with the implicit FEM package MSC MARC[®]. A schematic illustration of the FE model is presented in Fig. 2. To limit the number of elements, the domain is modeled as a quarter

of a cylinder and a symmetry plane (plane $x = 0$) has been introduced to allow the different nodes located in this plane to move only along the y -axis and the z -axis. A specific finite element mesh defined by 3 zones having different sizes of bilinear isoparametric 8-noded brick elements and using a linear interpolation function (full integration procedure) has been developed. In the contact area, the dimensions of the smallest element were about 0.2 times the estimated contact radius a_0 during the indentation and scratching phases. The size of the domain was chosen to be sufficiently large so that boundary effects did not influence the results, with $L_m/a_0 \geq 16$. The distance from an indentation to the edge of the sample (along the x -axis) was more than 6 times the contact radius of the indentation ($r_m/a_0 \geq 6$) and the thickness of the sample (along the y -axis) was at least 20 times the depth of penetration ($r_m/h \geq 20$). As boundary conditions, the x , y and z displacements of the nodes on the cylindrical surface were defined to be zero.

To reproduce elastic-plastic contacts, the problem was modeled as quasi-static and time-independent, with no influence of the strain rate. In order to reproduce the experimental tests, the kinematics may be divided into two distinct phases: (i) a first step, corresponding to indentation (along the y -axis) at a given maximum penetration depth h and (ii) a second step, corresponding to scratching (along the z -axis) at a constant relative velocity V_{tip} and the fixed indentation depth h . The length of the scratch L_R was chosen so that the normal and tangential loads applied to the indenter reached a steady state, with $L_R/a_0 \approx 6$. The elasto-plasticity was defined according to a bilinear von Mises model using isotropic hardening. In first approximation, a bilinear model with a constant tangent modulus provided a suitable fit for the material parameters. In the case of an elastic, linear hardening material, the stress - strain relation may be represented by:

$$\sigma = \begin{cases} E\varepsilon & (\sigma \leq \sigma_y) \\ \sigma_y + E_T(\varepsilon - \varepsilon_y) & (\sigma > \sigma_y) \end{cases} \quad (1)$$

where E is the elastic modulus, σ_y the yield stress, ε_y the yield strain satisfying $\varepsilon_y = \sigma_y/E$ and E_T the tangent modulus, corresponding to the constant work-hardening slope. The elastic modulus and the yield stress were fixed at $E = 3.5$ GPa, $\sigma_y = 100$ MPa and the tangent modulus E_T varied in order to get different ratios E_T/E in the range of 0.025 to 0.1. The contact between the spherical indenter and the surface of the sample was enforced using a penalty function method and a geometric description of slave and master surfaces. An isotropic Coulomb model was employed to include frictional effects. The contact model was implemented in the context of a finite sliding formulation, where arbitrary sliding and rotation between the surfaces could occur. For the ratio $a/R = 0.3$, scratch simulations were performed for different values of the true friction coefficient in the range of 0 to 0.7, assumed to be constant and independent of the contact pressure.

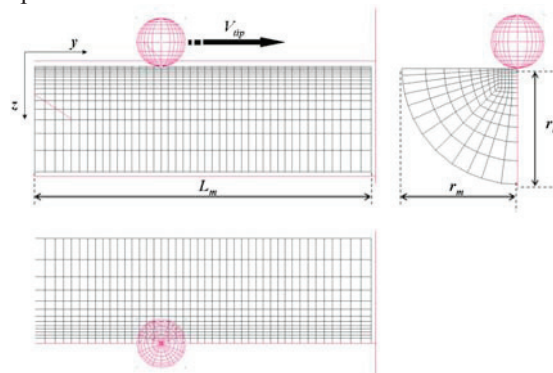


Fig. 2. FE mesh used in the simulation of scratching for a geometrical strain $a/R = 0.3$.

3. Results and discussion

3.1. Definition of the average plastic strain during scratch experiment

The main problem in the identification of the rheological parameters of a given polymeric surface using scratch experiment is the definition of strain imposed during tests, called the representative strain. Recently Gauthier *et al.* [7] have shown to a first approximation for several amorphous polymeric surfaces and during scratch experiments that the representative strain is proportional to the geometrical strain a/R , using the tangent function. However, using two dimensional finite element modelling (FEM), elliptical contact pressure and shear stress distributions were used to model the contact between a spherical tip and a polymeric surface. Numerical simulations were performed to locate the boundaries (i) between elastic and elastic-plastic contact and (ii) between elastic-plastic and plastic contact [7]. The numerical results indicate that for a given normalised contact pressure, the contact yielding depends on the local friction coefficient. Thus, for a given tip radius, the yielding of the contact depends on both the normal load which governs the ‘geometrical contact strain’ (i.e. the ratio a/R) and the local friction coefficient μ_{loc} . As performed in previous studies [8, 9], the average equivalent plastic strain in this representative volume can be estimated using the following relationships:

$$\varepsilon_{av}^p = \frac{1}{V_p} \sum_{i=1}^m \varepsilon_i^p \Delta V_i \quad (2)$$

where ε_i is the equivalent plastic strain at the centroid of element i , ΔV_i is the volume of the element i and m is the total number of elements used to calculate the average plastic strain. Thus, V_p is the plastically deformed volume in the representative right angled parallelepiped. Note that only elements in the representative volume, whose centroidal equivalent plastic value is above 0.002, are used in order to estimate the plastically deformed volume V_p . Similar methods [8, 10] have been previously employed, for determining the average plastic strain from numerical simulations of indentation and scratching with a conical indenter assuming frictionless contact. The main difference between this study and these two previous works deals with the definition of the representative volume.

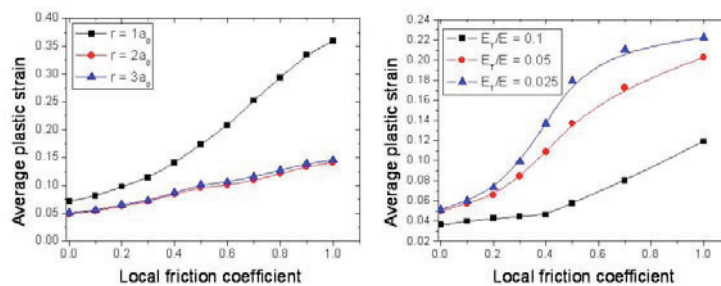


Fig. 3. Average plastic strain as a function the local friction determined using Eq. (2) (a) for different sizes of the representative volume and (a) for different ratios E_t/E , showing the influence the strain hardening ability

Using Eq. (2), the value of the average plastic strain in the contact during scratch is dependent on the characteristic size of the representative volume (Fig. 3). However, rapidly, for a radius of the representative volume greater than two times the contact radius between the tip and the deformed surface, the average plastic for a given local friction appears to be constant. We decided to calculate the average plastic strain using a representative volume with a radius $r = 3a_0$, with a_0 , the contact radius estimated for frictionless contact for $\mu_{loc} = 0$. With the increase of the local friction the average plastic strain imposed

during contact increase. However, for a given local friction coefficient, the average plastic strain appears to be depend on the rheological behavior of the tested material, especially the strain hardening [11].

3.2. Apparent and ploughing friction coefficients

In this FE study, the interface between the rigid indenter and the deformable surface was not assumed to be frictionless. As already reported by Lafaye *et al.* [12], the apparent friction coefficient μ_{app} defined by the ratio F_t/F_n is as a first approximation for scratching the sum of the local friction coefficient μ_{loc} and the ploughing term μ_{def} due to irreversible deformation. The apparent friction appears to be equal to the local friction coefficient only for symmetric contact, corresponding to elastic sliding. However, for asymmetric contact (elastic-plastic and fully plastic scratching), the ploughing term can not be neglected and the apparent friction coefficient is greater than the local friction coefficient. A similar description of the overall friction coefficient μ_{app} has been used by Subhash and Zhang [13]. In the case of single-pass scratch tests on bilinear elastic-plastic material using conical indenters with different apical angles, they have shown by FEM that the apparent friction coefficient is function of an adhesive term, related to the interfacial friction coefficient μ_{loc} and of a ploughing term, due to the resistance as the indenter plows into the material, and then related to the apical angle.

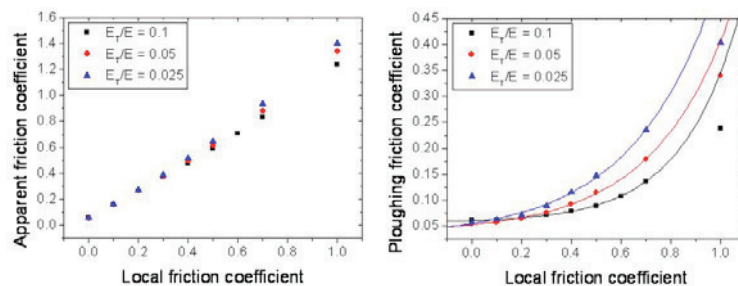


Fig. 4. (a) apparent friction coefficient and (b) ploughing friction coefficient as a function of the local friction coefficient for different ratios E_T/E

Figure 4 shows in first approximation that the apparent friction increases linearly as a function of the local friction, with no real influence of the strain hardening of the tested material. When estimated the ploughing term, an effect of the ratio E_T/E can be observed especially for high value of the local friction. The ploughing friction coefficient increases exponentially, especially for materials exhibiting low strain hardening ability. It is interesting to note the correlation between the evolution of the average plastic strain in Fig.3 and the evolution of the ploughing term, as a function of the local friction and the ratio E_T/E .

3.3. Contact pressure

Using FEM, we are able to estimate the maximum pressure imposed during the contact between the moving tip and the deformed surface. Classically, during experiments [2,3], we estimate using normal applied load and the projected contact area, the average contact pressure. In figure 5, we have plotted the evolution of the maximum normal contact pressure, normalized by the yield stress σ_Y as a function of the local friction coefficient for the different ratios E_T/E . As observed previously in figures 3 and 4, the contact pressure increases progressively with the local friction to reach very high value for values of μ_{loc} greater than 0.7. We observe for a given local friction coefficient that the imposed contact pressure is lower for material with low strain hardening ability, that exhibits high level of plastic strain (Fig. 3) and high ploughing friction coefficient (Fig. 4). In figure 5, we have represented the evolution of the

normalized maximum contact pressure as a function of the average plastic strain estimated using Eq. 2. Figure 5 shows for a given ratio E_T/E that the maximum pressure increases linearly as a function of the average plastic strain, and the slope of the linear regression is proportional to the imposed ratio E_T/E .

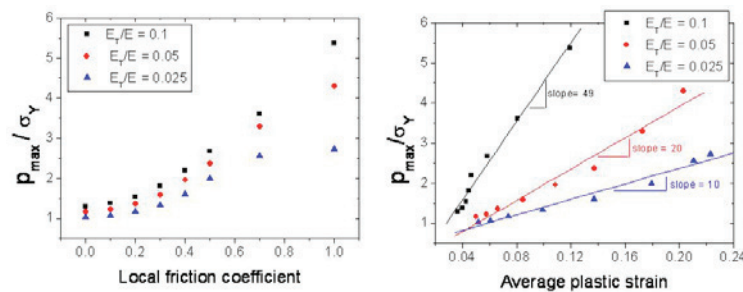


Fig. 5. Maximum normal contact pressure normalized by the yield stress as a function of (a) the local friction coefficient and (b) the average plastic strain for different ratios E_T/E .

4. Conclusion

This paper shows clearly how to improve the scratch and then resistance of polymeric surfaces. In one hand, specific surface treatments have to be imagined in order to reduce the local friction that modifies the nature of the contact whatever the rheological parameters, especially the equivalent plastic strain in the contact area and then in the residual groove. In the other hand, mechanical properties of polymeric surfaces have to be increased by fillers or nanoparticles, located in the near surface region, especially to improve the strain hardening ability that reduces the equivalent plastic strain for a higher imposed normal contact pressure, especially at high local friction coefficient.

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